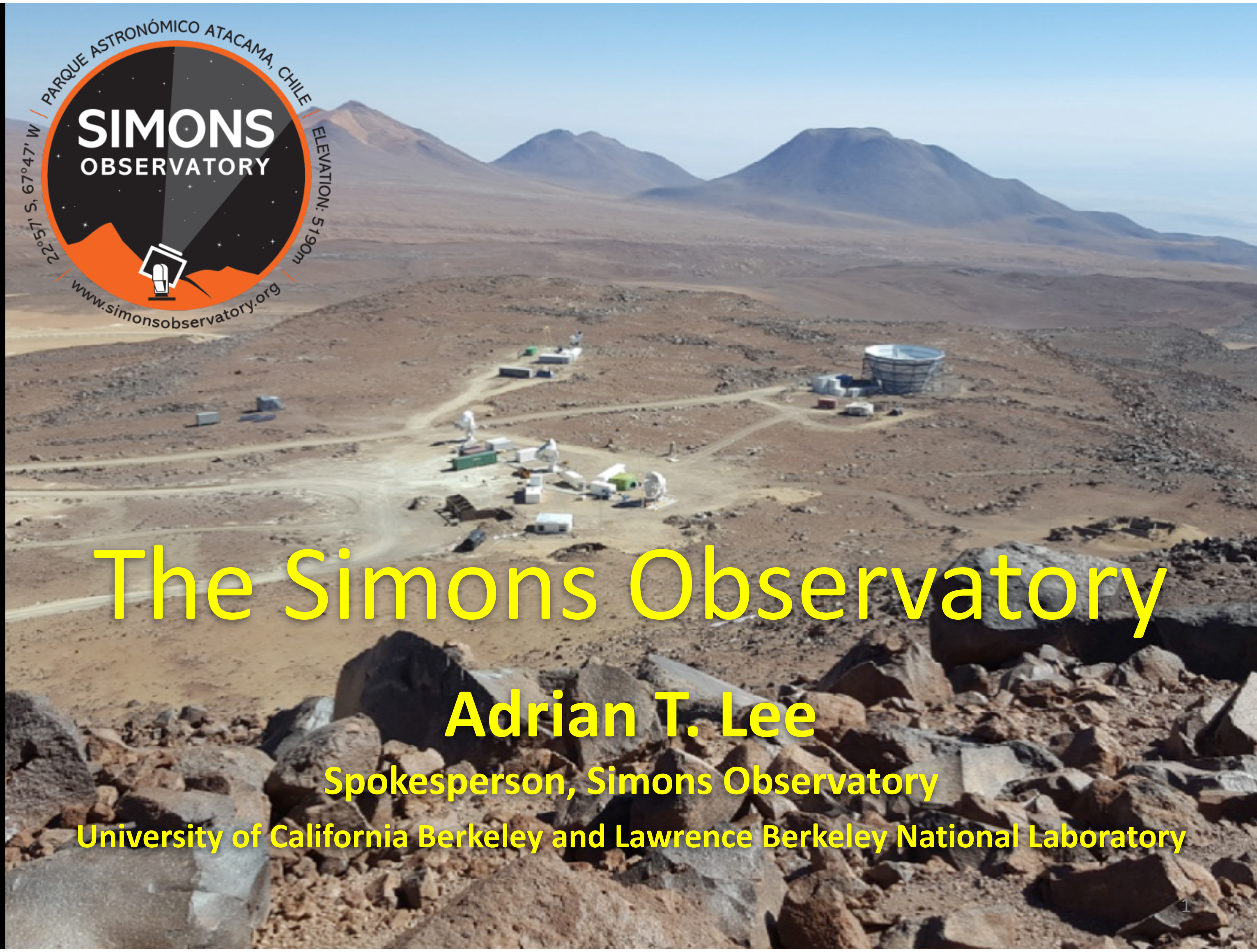



# The Simons Observatory

**Adrian T. Lee**

**Spokesperson, Simons Observatory**

**University of California Berkeley and Lawrence Berkeley National Laboratory**

# The Simons Observatory Collaboration

United States
- Arizona State University
- Carnegie Mellon University
- Center for Computational Astrophysics
- Cornell University
- Florida State
- Haverford College
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Southern California
- West Chester University
- Yale University

Japan
- KEK
- IPMU
- Tohoku
- Tokyo

- **10 Countries**
- **40+ Institutions**
- **160+ Researchers** → **~200**

Canada
- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Simon Fraser University
- University of British Columbia

Chile
- Pontificia Universidad Catolica
- University of Chile

Europe
- APC – France
- Cambridge University
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

South Africa
- Kwazulu-Natal, SA

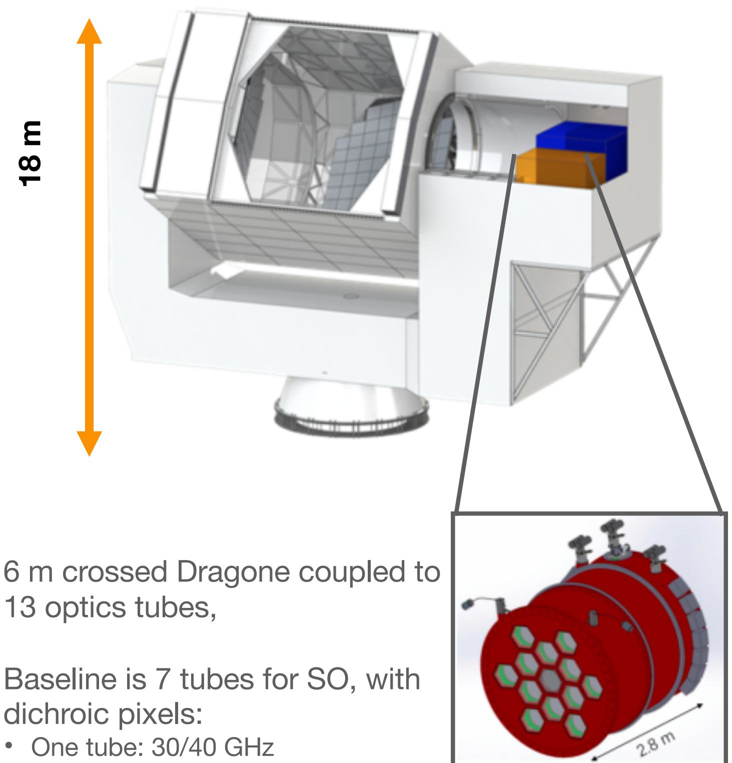
Australia
- Melbourne

Middle East
- Tel Aviv


HEARST·MEMORIAL·MINING·BUILDING

# The Simons Observatory instruments and technology

## Large Aperture Telescope

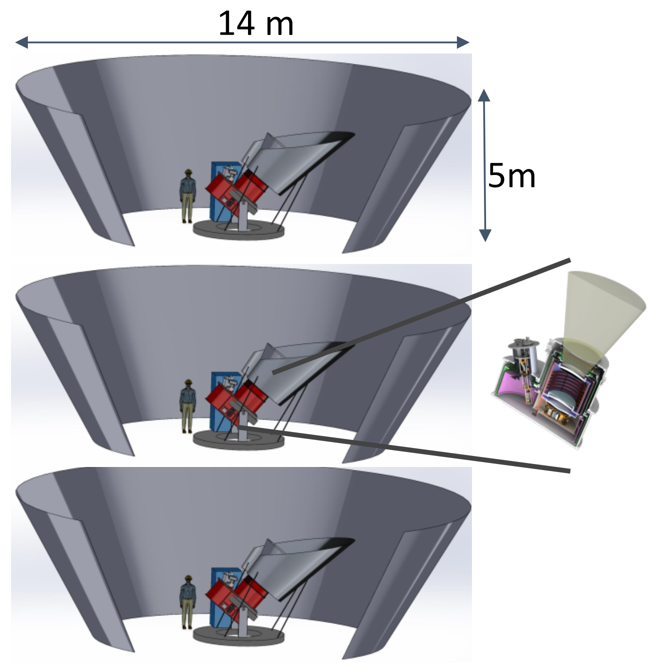



6 m crossed Dragone coupled to 13 optics tubes,

Baseline is 7 tubes for SO, with dichroic pixels:

- One tube: 30/40 GHz
- Four tubes: 90/150 GHz
- Two tubes: 220/270 GHz

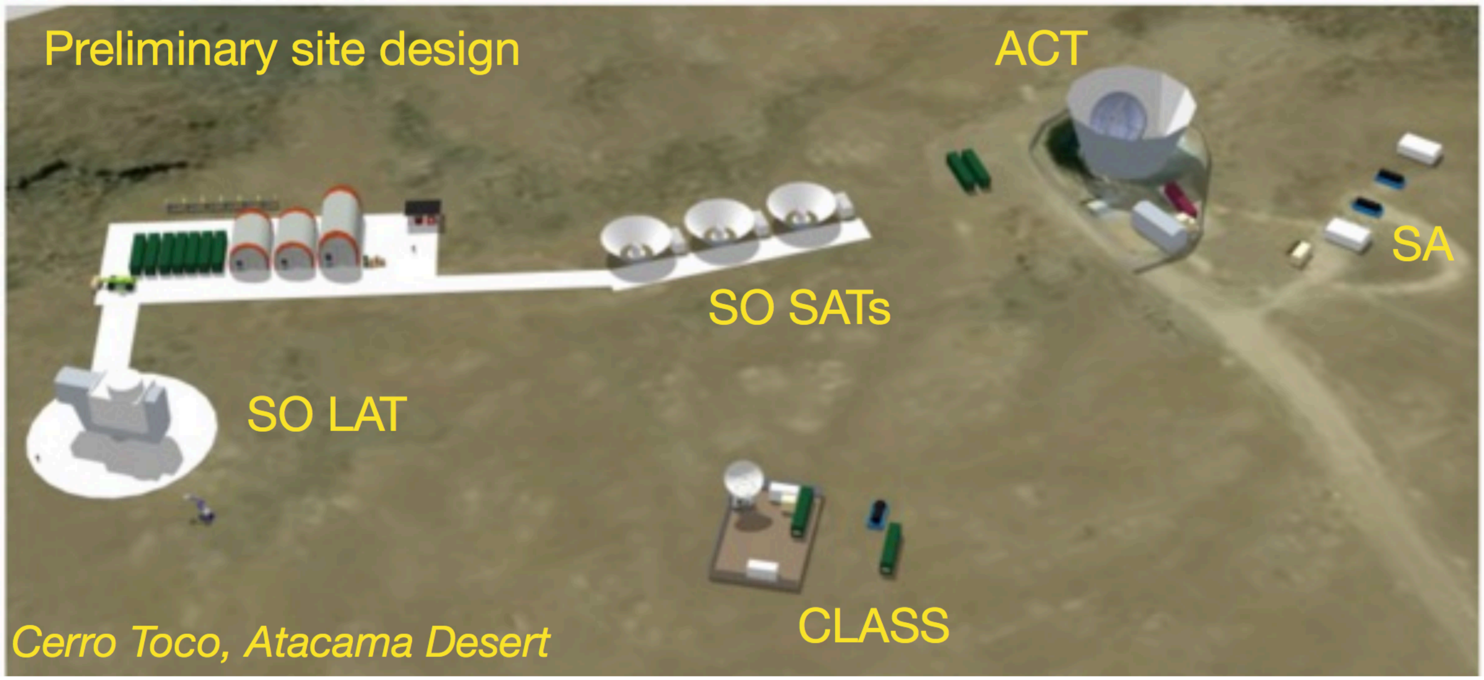
## Small Aperture Telescopes




Three refractors 42 cm in diameter, rotating half-wave plate.
Dichroic pixels:
30/40 | 90/150 | 220/270 GHz

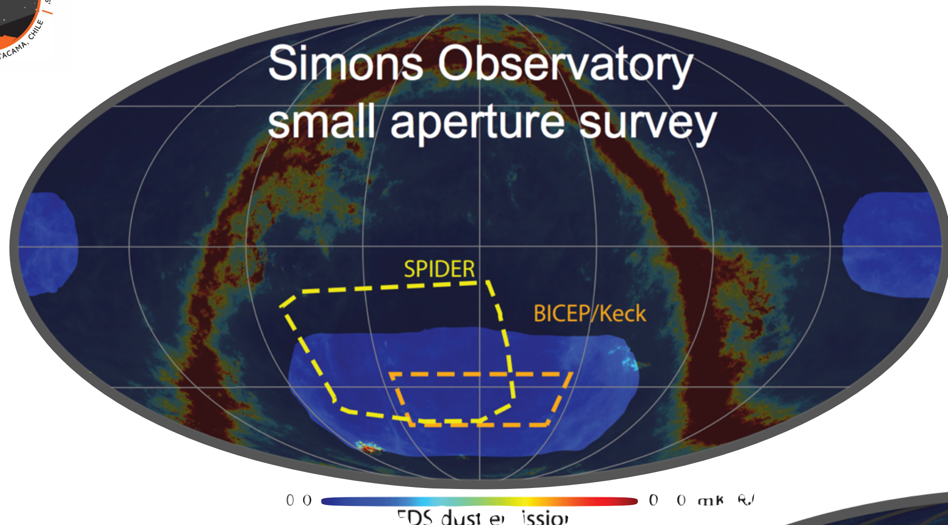
## Simons Observatory Layout

One 6m Large Aperture Telescope
Three 0.5m Small Aperture Telescopes
Five-year survey planned 2021-26, six frequencies 30-280 GHz



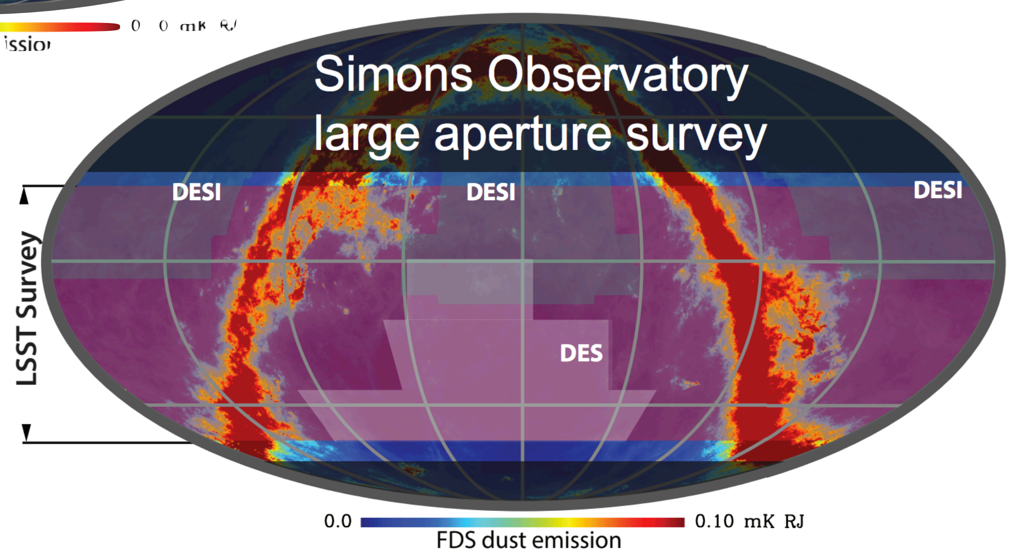

Large telescope: resolution needed for all science goals except tensor-to-scalar ratio
Small telescopes: lower noise at the few-degree-scale B-mode signal, for tensor-to-scalar ratio

# Anticipated Sky Coverage




effective $f_{sky}$ ~ 10%

for SO noise and coverage, dedicated delensing survey not required




effective $f_{sky}$ ~ 40%

maximal overlap w/ LSST, large overlap w/ DESI

# Anticipated Noise Performance

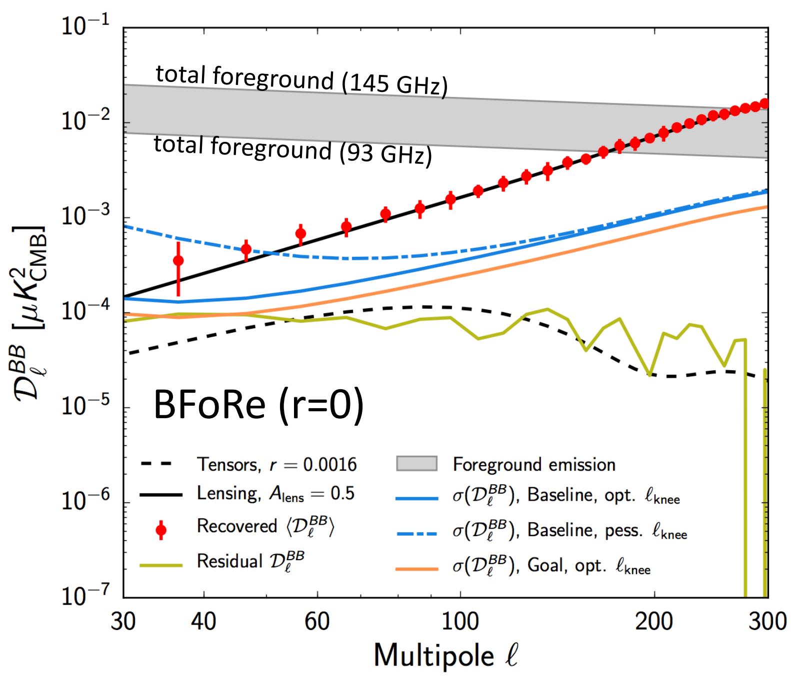
| | | SATs ($f_{\rm sky} = 0.1$) | | | | LAT ($f_{\rm sky} = 0.4$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Freq. [GHz] | FWHM ($'$) | Noise (baseline) [$\mu$K-arcmin] | | Noise (goal) [$\mu$K-arcmin] | FWHM ($'$) | Noise (baseline) [$\mu$K-arcmin] | | Noise (goal) [$\mu$K-arcmin] |
| LF | 27 | 91 | 35 | | 25 | 7.4 | 71 | | 52 |
| | 39 | 63 | 21 | | 17 | 5.1 | 36 | | 27 |
| MF | 93 | 30 | 2.6 | 2 μK-amin | 1.9 | 2.2 | 8.0 | 6 μK-amin | 5.8 |
| | 145 | 17 | 3.3 | | 2.1 | 1.4 | 10 | | 6.3 |
| HF | 225 | 11 | 6.3 | | 4.2 | 1.0 | 22 | | 15 |
| | 280 | 9 | 16 | | 10 | 0.9 | 54 | | 37 |

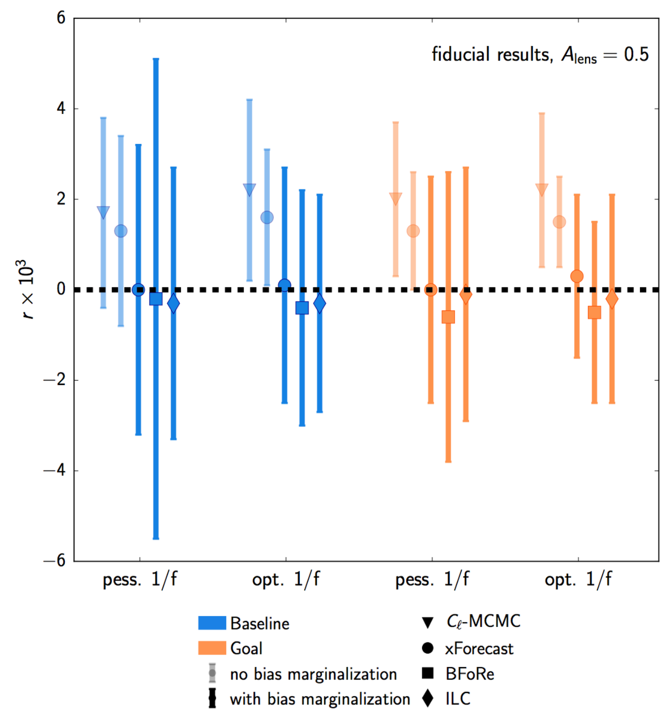
White noise levels for 5-yr survey; also include atmospheric noise model and combine with Planck

**SO SAT Science: Primordial Tensor Modes**

## SAT BB forecasting based on full-sky simulated maps (PySM) w/ multiple sets of realistic foregrounds

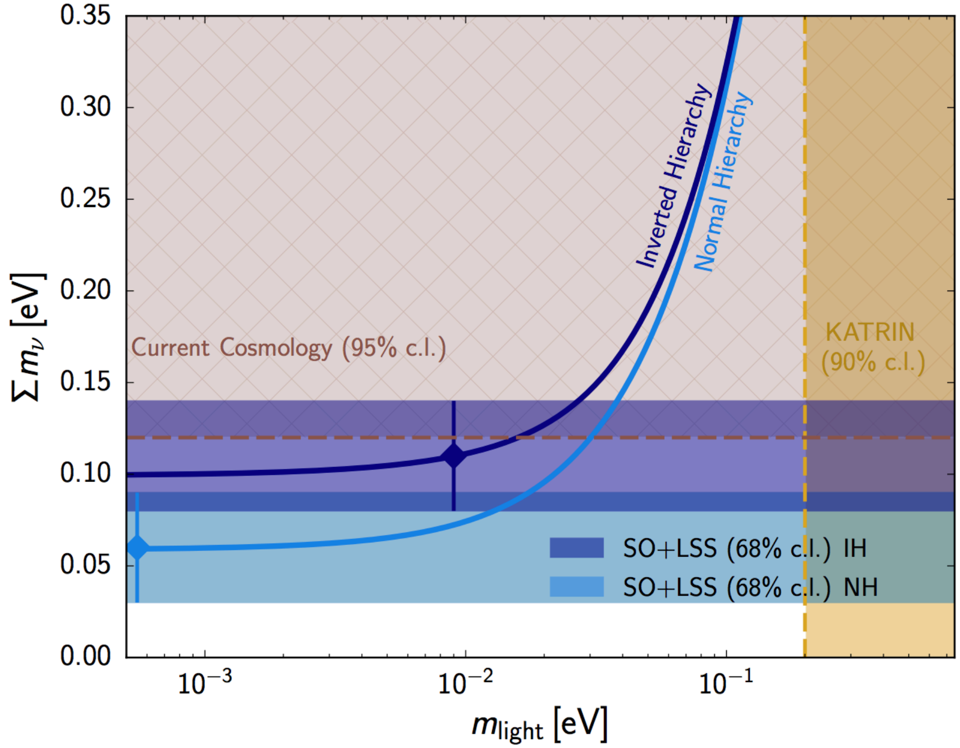
Sky models are combined with SO SAT noise model, then coupled to several foreground mitigation schemes (cross-spectrum analysis, xForecast, BFoRe, harmonic-space ILC) to infer *r*



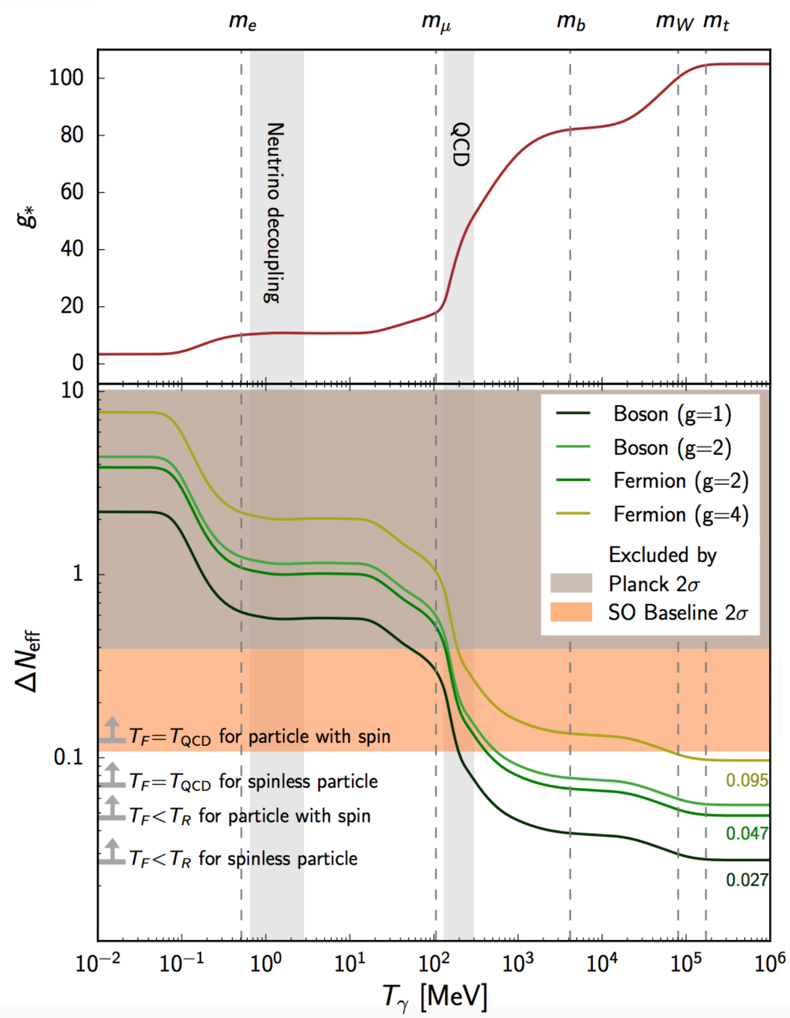
SO LAT Science: Neutrino Masses

Constraints derived from CMB lensing power spectrum (+DESI BAO), tSZ cluster counts (+LSST WL), and tSZ power spectrum (+DESI BAO)




σ(ΣMν) = 0.04 eV → 0.02 eV w/ CV-limited τ

# SO LAT Science: Light Relics




SO can detect any particle with spin that decoupled after the start of the QCD phase transition (at 2σ)

$\sigma(N_{\mathrm{eff}}) = 0.07$

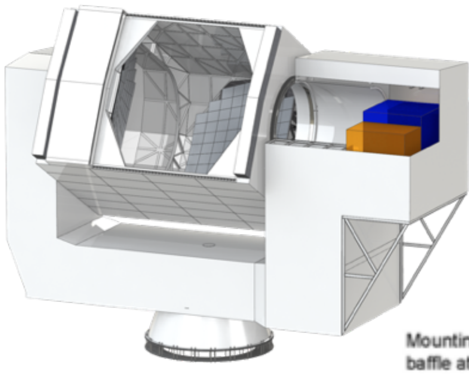
Forecasts are strongly robust to foregrounds (driven by TE + EE)

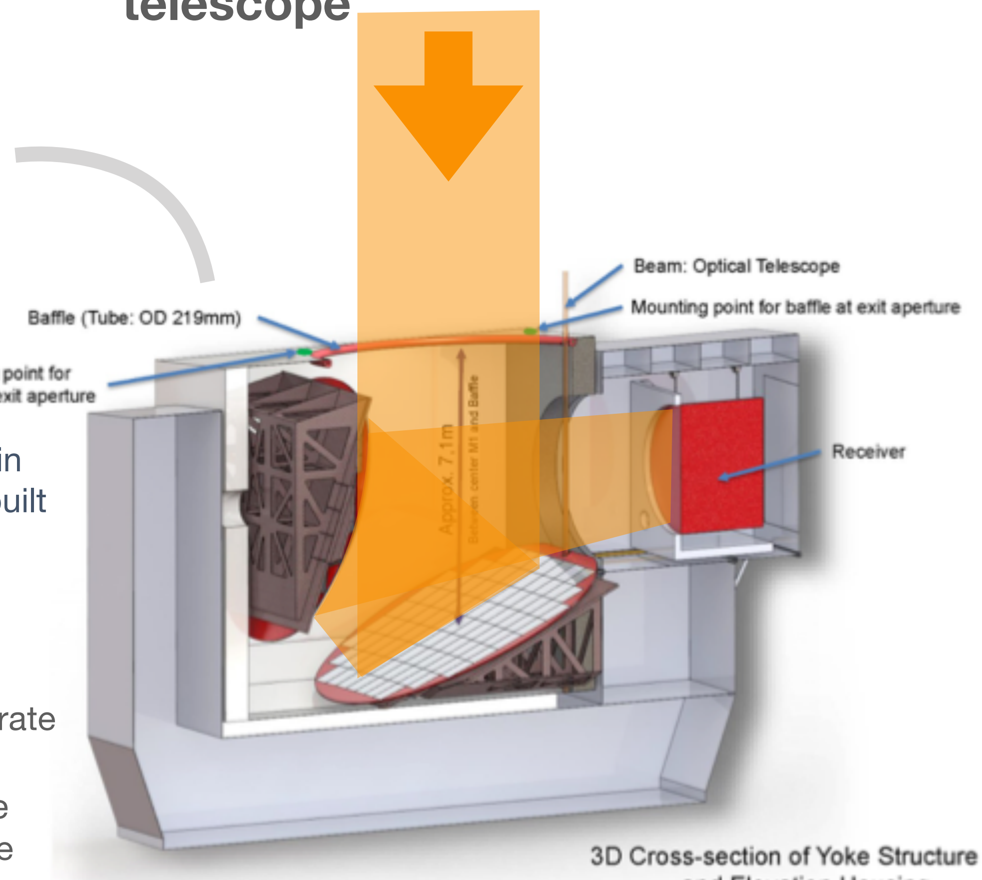
Other damping tail science:
- BBN ($Y_p$)
- $H_0$ improvement (~2x)
- Dark matter interactions
- Ultra-light axions
- and more

Table 1: Summary of SO key science goals[a]

| | Current[b] | SO-Nominal (2022-27) | | Method[d] | SWP |
|---|---|---|---|---|---|
| | | Baseline | Goal | | |
| **Primordial perturbations** (§2.1) | | | | | |
| $r$ ($A_L = 0.5$) | 0.03 | 0.003 | 0.002[e] | BB + external delensing | [28] |
| $n_s$ | 0.004 | 0.002 | 0.002 | TT/TE/EE | [28] |
| $e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$ | 3% | 0.5% | 0.4% | TT/TE/EE | [30] |
| $f_{\mathrm{NL}}^{\mathrm{local}}$ | 5 | 3 | 1 | $\kappa\kappa \times$ LSST-LSS | [23] |
| | | 2 | 1 | kSZ + LSST-LSS | |
| **Relativistic species** (§2.2) | | | | | |
| $N_{\mathrm{eff}}$ | 0.2 | 0.07 | 0.05 | TT/TE/EE + $\kappa\kappa$ | [16] |
| **Neutrino mass** (§2.3) | | | | | |
| $\Sigma m_\nu$ (eV, $\sigma(\tau) = 0.01$) | 0.1 | 0.04 | 0.03 | $\kappa\kappa$ + DESI-BAO | [11] |
| | | 0.04 | 0.03 | tSZ-N $\times$ LSST-WL | |
| $\Sigma m_\nu$ (eV, $\sigma(\tau) = 0.002$) | | 0.03[f] | 0.02 | $\kappa\kappa$ + DESI-BAO + LB | |
| | | 0.03 | 0.02 | tSZ-N $\times$ LSST-WL + LB | |
| **Beyond standard model** (§2.4) | | | | | |
| $\sigma_8(z = 1 - 2)$ | 7% | 2% | 1% | $\kappa\kappa$ + LSST-LSS | [31] |
| | | 2% | 1% | tSZ-N $\times$ LSST-WL | |
| $H_0$ ($\Lambda$CDM) | 0.5 | 0.4 | 0.3 | TT/TE/EE + $\kappa\kappa$ | [3] |
| **Galaxy evolution** (§2.5) | | | | | |
| $\eta_{\mathrm{feedback}}$ | 50-100% | 3% | 2% | kSZ + tSZ + DESI | [2] |
| $p_{\mathrm{nt}}$ | 50-100% | 8% | 5% | kSZ + tSZ + DESI | [2] |
| **Reionization** (§2.6) | | | | | |
| $\Delta z$ | 1.4 | 0.4 | 0.3 | TT (kSZ) | [1] |

# The Simons Observatory Large Aperture telescope

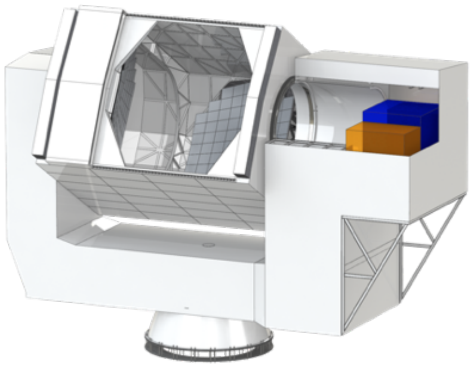





3D Cross-section of Yoke Structure and Elevation Housing (view towards M1)

- 6-meter telescope developed in collaboration with CCAT and built by Vertex
- 2-mirror design with a side-looking camera.
- The camera rotates with the elevation axis, and has a separate camera-boresite rotation.
- The back of the camera can be accessed while installed on the telescope.
- The telescope is capable of coupling to more than 100,000 detectors

# The Simons Observatory Large Aperture Telescope



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- The back of the camera can be accessed while installed on the telescope.
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**3 PT420 coolers**

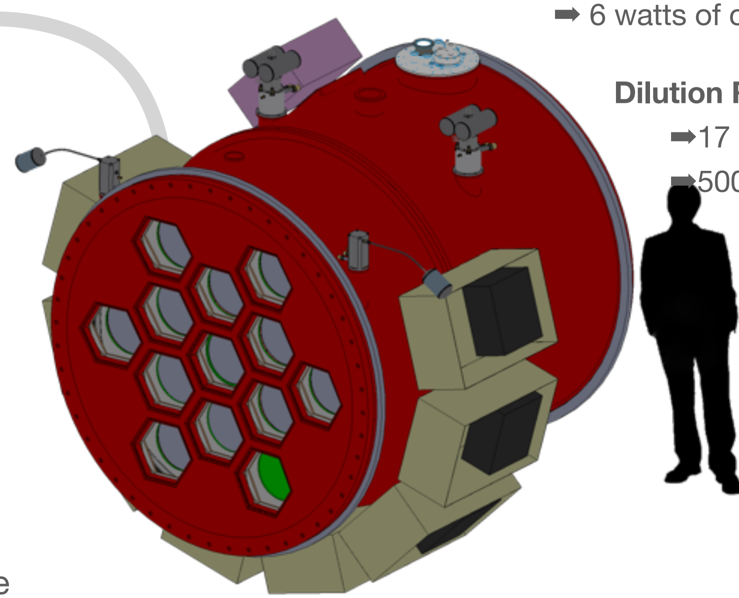
➡ 165 watts of cooling at 40 K

➡ 6 watts of cooling at 4 K

**Dilution Refrigerator**

➡17 mW at 1K

➡500 uW at 100 mK

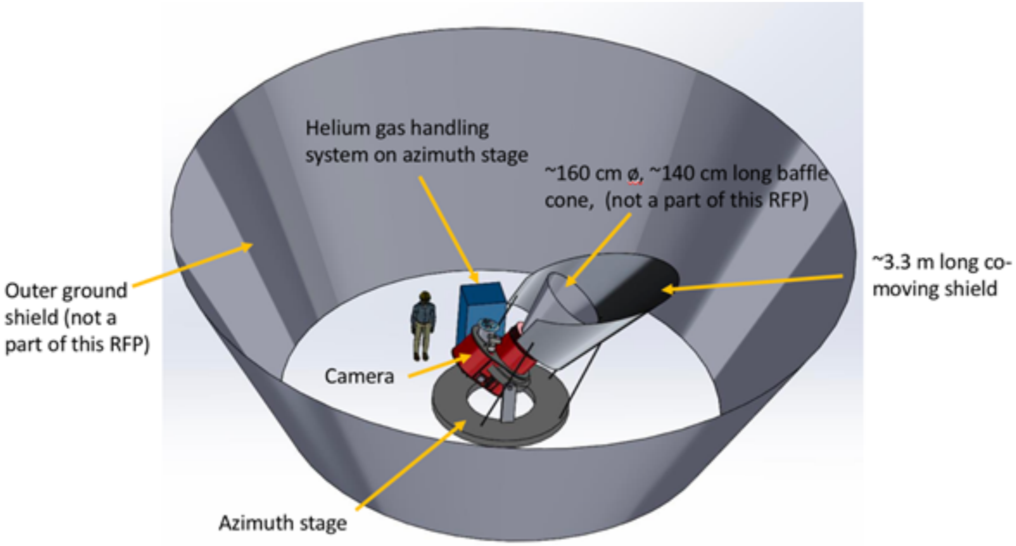


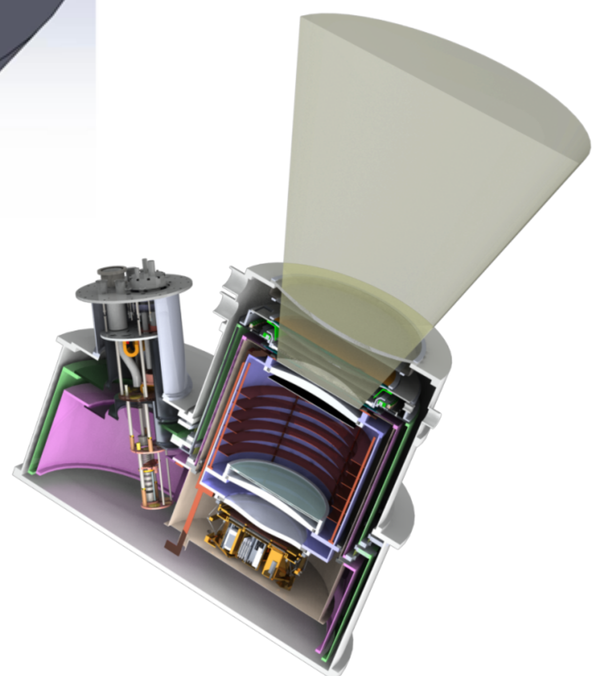
**total weight ~ 5000kg (!)**
when populated with 13 tubes

- 1200 kg cooled to 4K
- 200 kg cooled to 100 mK

**Under contract for Telescope, have multiple vendor quotes for receiver**

# The Simons Observatory Small Aperture Camera

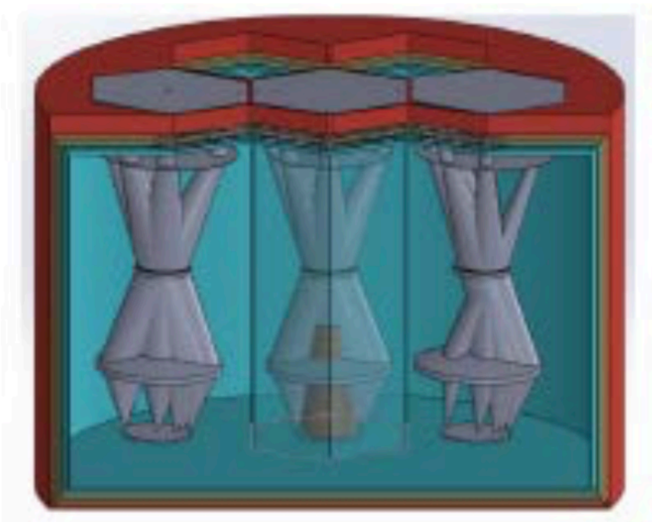


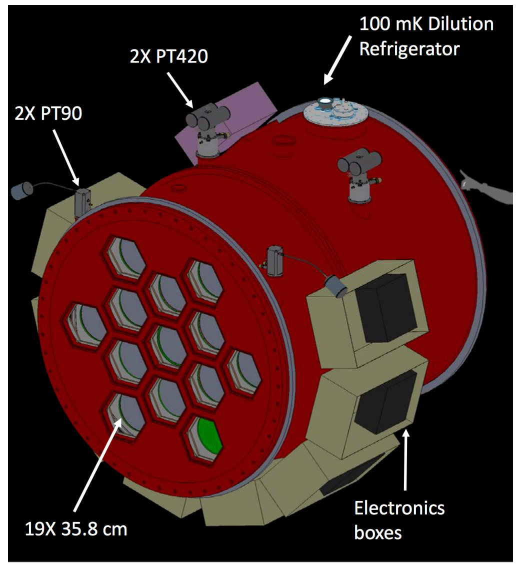
- 42 cm aperture size, 35 degree FoV
- 40,000 detectors for SO
- continuously rotating HWP
- **Ground screen 4.9 m high, 16 meters in diameter**

# SO Instrument Progress 2019

# Large Aperture Telescope Receiver (LATR)



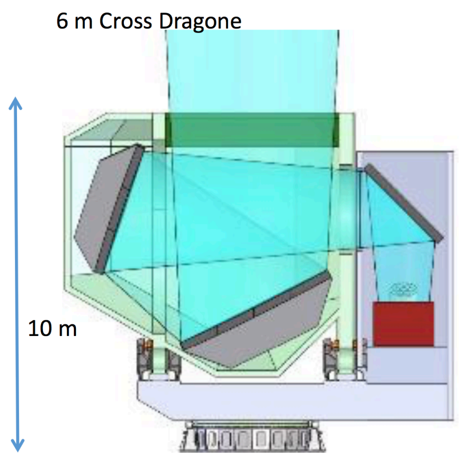
2017

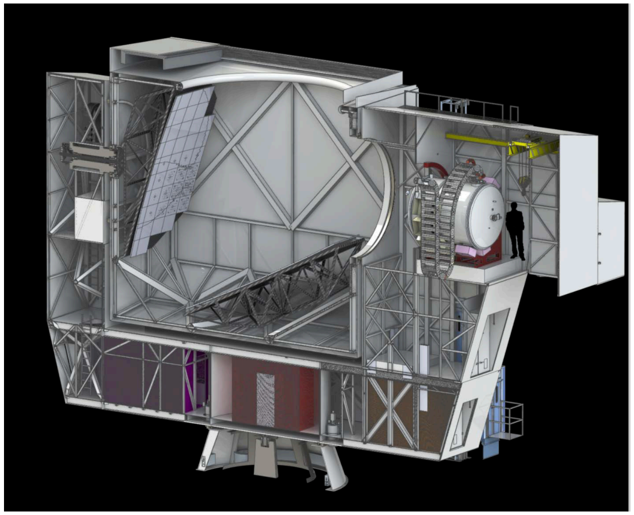



2018


2019

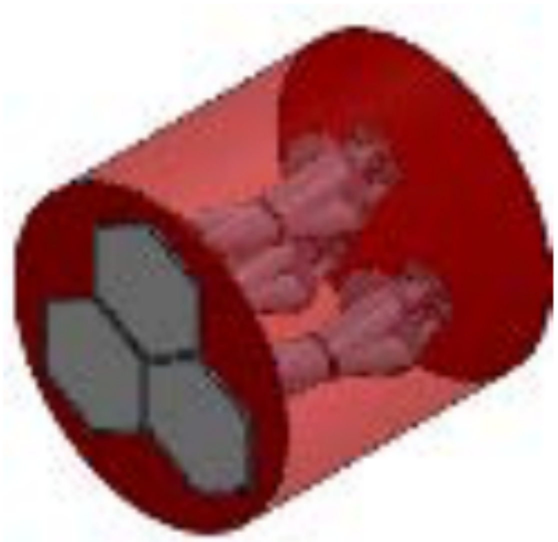
# Large-Aperture Telescope

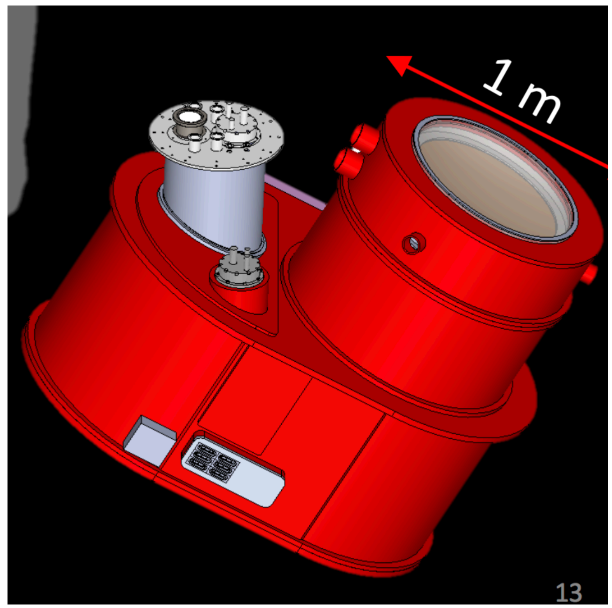


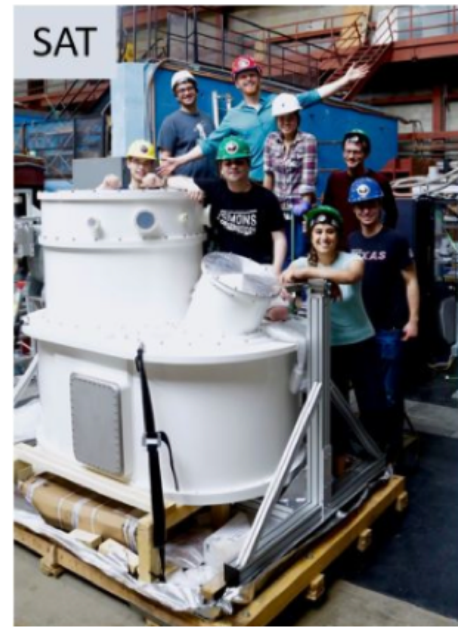



2017 2018 2019

# Small Aperture Telescope (SAT)

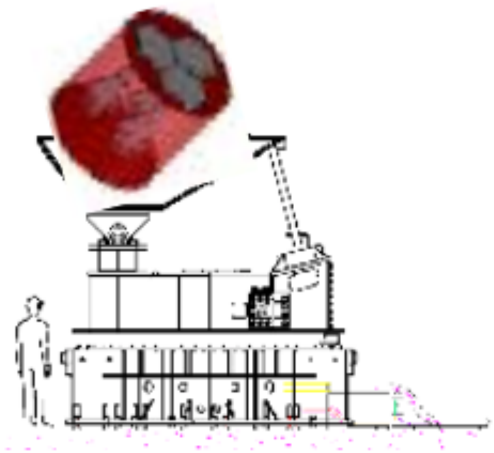




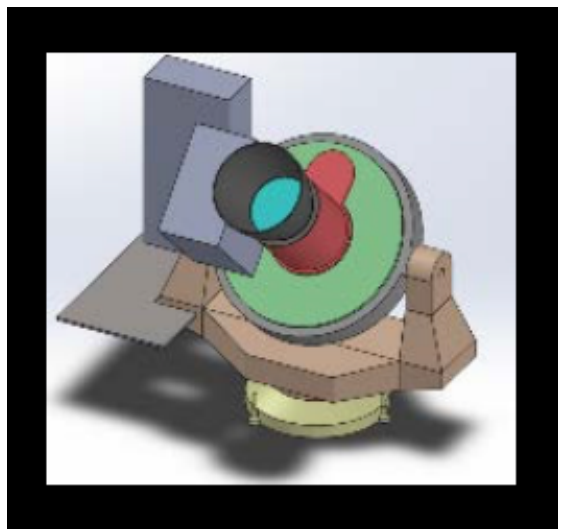




2017 2018 2019

# Small Aperture Telescope Platform (SATP)



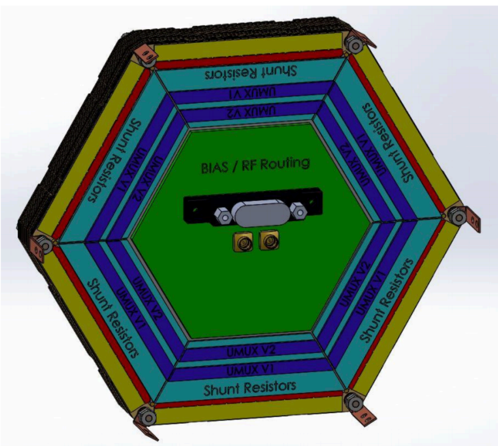
2017



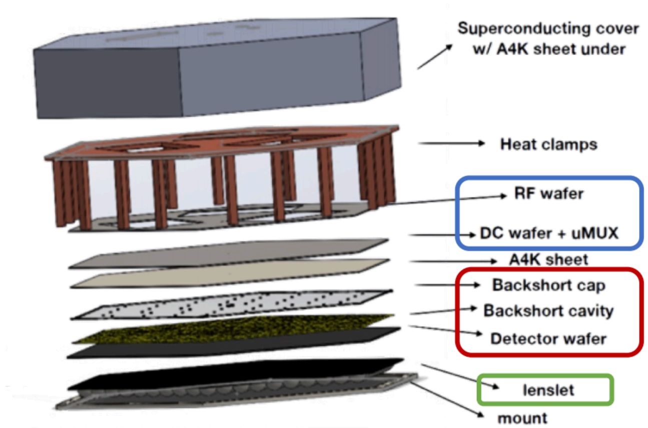
2018


2019

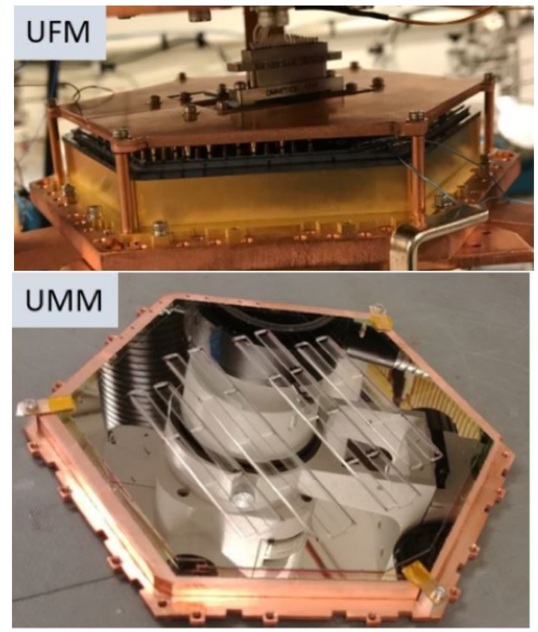
# Universal Focal Plane Module (UFM)



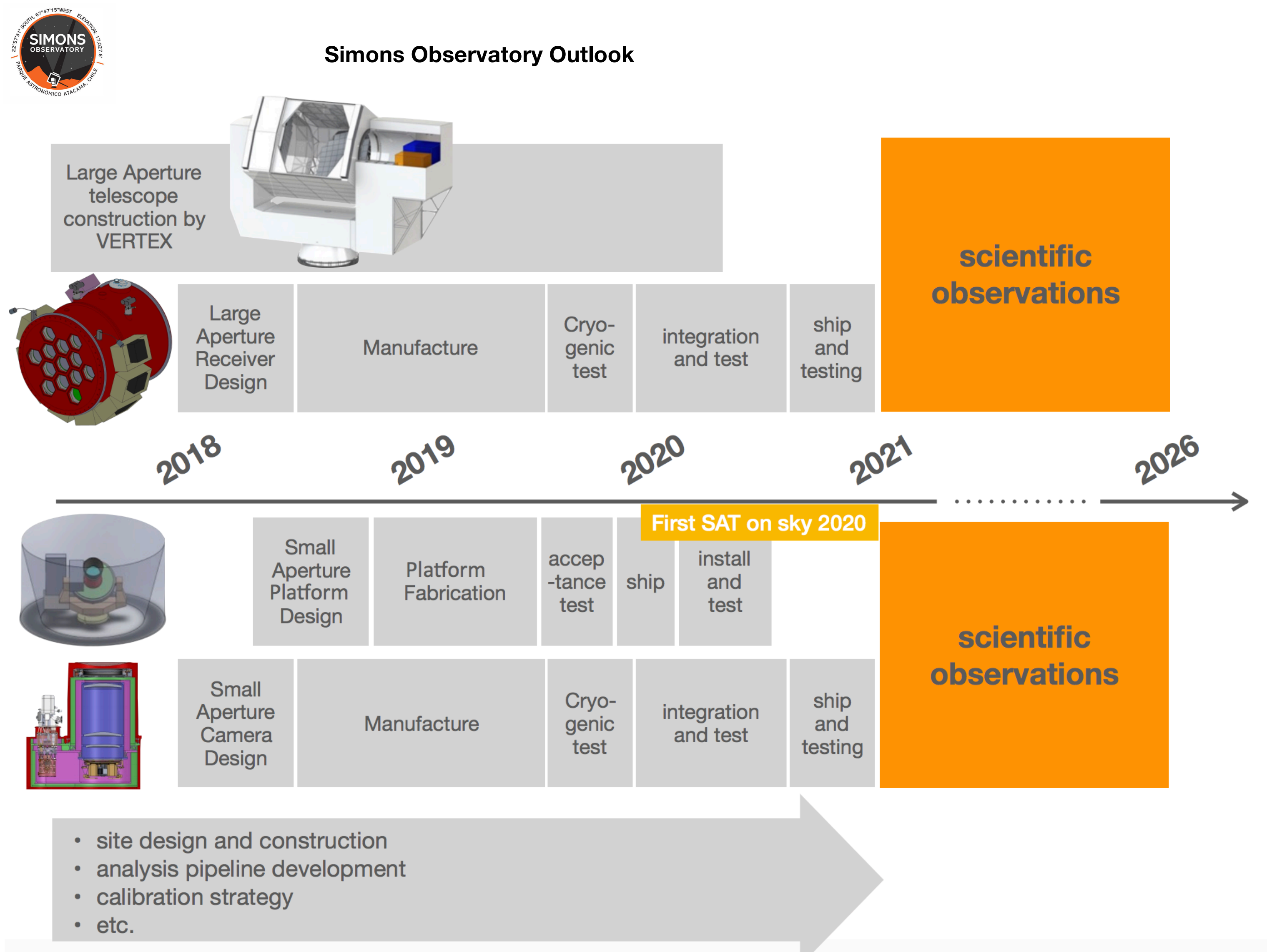

2017




2018




2019

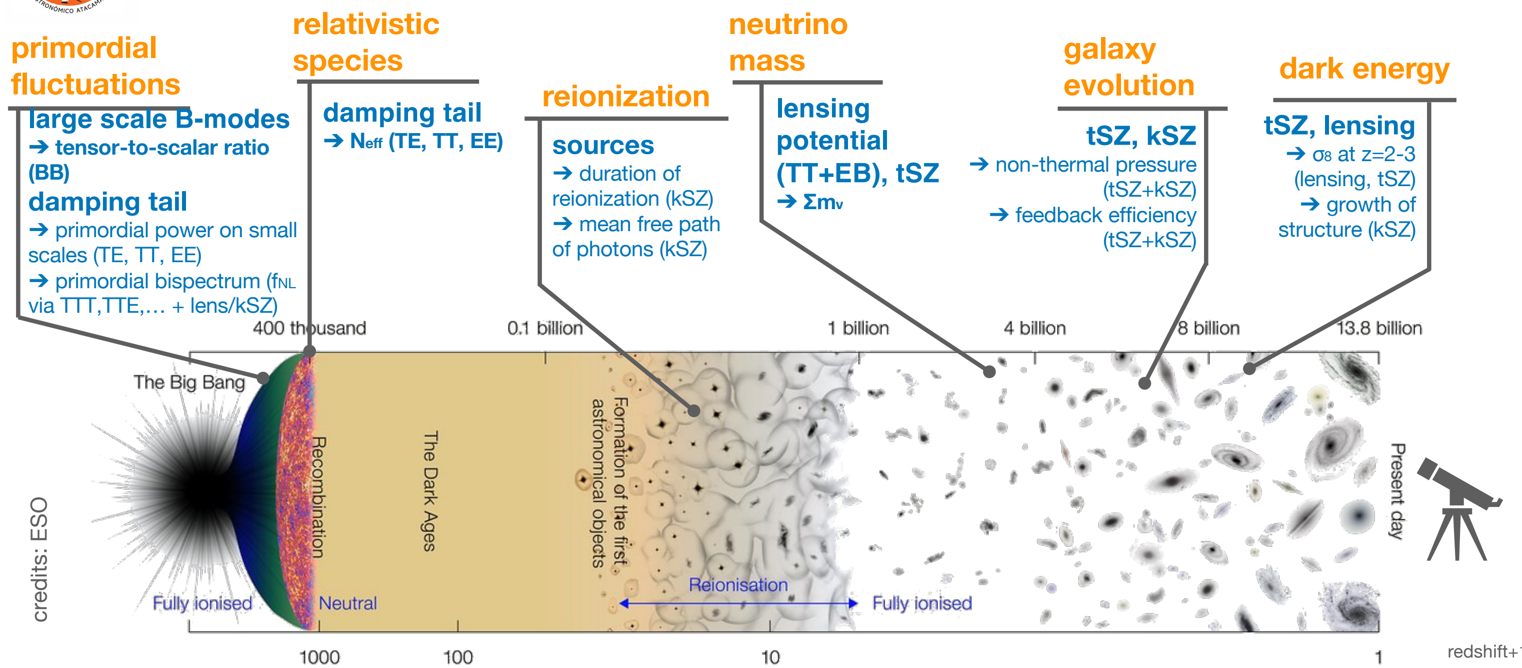

Simons Observatory Outlook
Large Aperture telescope construction by VERTEX
Large Aperture Receiver Design
Manufacture
Cryo-genic test
integration and test
ship and testing
scientific observations
2018
2019
2020
2021
2026
First SAT on sky 2020
Small Aperture Platform Design
Platform Fabrication
accep-tance test
ship
install and test
scientific observations
Small Aperture Camera Design
Manufacture
Cryo-genic test
integration and test
ship and testing
site design and construction
analysis pipeline development
calibration strategy
etc.

# European Context

- Simons Observatory in construction
  - By mid 2021: First light for SAT#1
  - By early 2023: Construction complete
- European collaborators playing essential role
  - Proposals to extend hardware role (e.g. Michael Brown's talk next)
  - Further collaborative ideas very welcome!
- SO and CMB-S4 cooperation
  - Large team overlap and strong contributions to CMB-S4 reference design
  - Technical Sharing from SO to CMB-S4

# Backup

**Simons Observatory Science Goals and Probes**




Additional science includes (but is not limited to):

- helium fraction, cosmic birefringence, primordial magnetic fields
- high-redshift clusters
- dark matter annihilation and interactions
- isocurvature
- calibration of multiplicative shear bias (e.g., for LSST)
- new sample of dusty star-forming galaxies
- transient sources
- cosmic infrared background

THE SIMONS OBSERVATORY:
SCIENCE GOALS
AND FORECASTS

**1808.07445**

# Science and Planning - 2018

V0 – Initial Instrument Concepts – Oct. 2016
V1 – Detailed Instrument Concept – Jan. 2017
V2 – Frequency Balance – June 2017
V3 – Sensitivity Budget and Tracking - 2018

## Science Traceability Matrix

| ID | Title | Parameter | Baseline | Goal | Current | Method |
|---|---|---|---|---|---|---|
| SR-1a | **Primordial fluctuations** | **r** | **0.003** | **0.002** | **0.04** | **BB** |
| SR-1b | | P(k=0.2 h/Mpc) | **0.5%** | **0.4%** | 6% | T/E |
| SR-1c | | fnl | **3** | **1** | 5 | kk+LSST+3-pt |
| SR-2 | Relativistic Species | $N_{eff}$ | **0.07** | **0.05** | 0.11 | T/E |
| SR-3 | Neutrino mass | $m_{\nu}$ (eV) | **0.04** | **0.03** | 0.1 | kk+DESI |
| | | | **0.04** | **0.03** | | tSZ-N+LSST |
| | | | **0.05** | **0.04** | | tSZ-Cl+DESI |
| SR-4 | Dark Energy | $sigma_8(z=2-4)$ | **3%** | **2%** | 7% | kk+LSST |
| | | | **3%** | **2%** | | tSZ+LSST/k |
| SR-5a | Galaxy Evolution | feedback efficiency in massive halos | **6%** | **3%** | 50-100% | tSZ+kSZ |
| SR-5b | | non-thermal pressure in massive halos | **15%** | **12%** | 50-100% | tSZ+kSZ |
| SR-6 | Reionization | duration delta(z) | **0.6** | **0.3** | 1.4 | T/E (kSZ) |

## Measurement Requirements - SAT

| ID | Title | Description | Trace |
|---|---|---|---|
| MR-1S | #Bands | 30, 40, 90, 150,220, 280 GHz | SR-1a |
| MR-2S | angular resolution | 90, 60, 30, 30, 30, 30' | SR-1a |
| MR-3S | sensitivity white noise | (Baseline) 35, 22, 2.6, 3.3, 6.3, 16 uK/amin | SR-1a |
| | | (Goal) 25, 17, 1.9, 2.1, 4.2, 10 uK/amin | |
| MR-4S | 1/f noise | knee l<25 | SR-1a |
| MR-5S | pol systematics | systematics below 40% of statistical errors | SR-1a |
| MR-6S | sky area | 10% effective sky area with low FG | SR-1a |

## Measurement Requirements - LAT

| ID | Title | Description | Trace |
|---|---|---|---|
| MR-1L | #Bands | 30, 40, 90, 150,220, 280 GHz | SR-3-6 |
| MR-2L | angular resolution | 7.5, 5.5, 2.2, 1.4, 1.0,1.0' | SR-3-6 |
| MR-3L | sensitivity white noise | (Baseline) 71, 36, 8.0, 10.0, 22, 54 uK/amin | SR-1b-6 |
| | | (Goal) 52, 27, 5.8, 6.3, 15, 38 uK/amin | |
| MR-4L | 1/f noise | knee l<1000 | SR-3-6 |
| MR-5L | pol systematics | systematics below 40% of statistical errors | SR-1b-6 |
| MR-6L | sky area | 40+% sky, overlapping with LSST (f=0.35-4), DESI (f=0.1) | SR-1b-6 |